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HIGH-SPEED ELECTRO-OPTIC ANALOG-TO-DIGITAL CONVERTER.(U)
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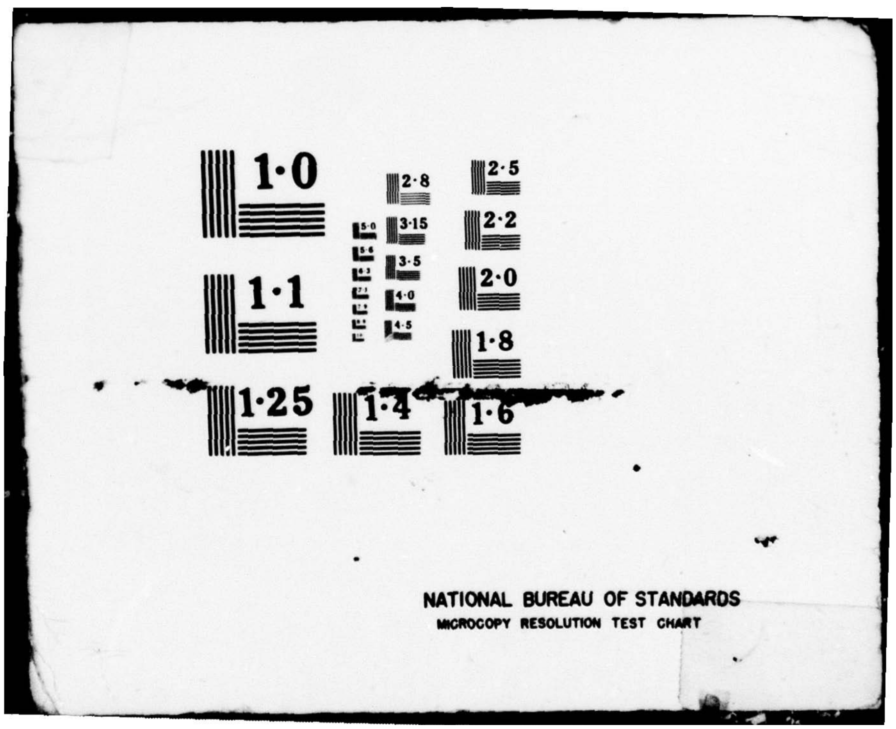
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HIGH-SPEED ELECTRO-OPTIC ANALOG-TO-DIGITAL CONVERTER

MJ Taylor
HF Taylor

October 1978

Final Report

Prepared for
Office of Naval Research

Approved for public release; distribution unlimited

NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CALIFORNIA 92152

NAVAL OCEAN SYSTEMS CENTER, SAN DIEGO, CA 92152

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Commander

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The periodic dependence of the output of an electro-optic intensity modulator on applied voltage can be utilized to perform A/D conversion. The feasibility of the concept has been demonstrated by such a modulator in a threshold circuit to simulate one bit channel of an A/D converter. The optical approach offers several potential improvements over present technique: faster conversion rates, fewer comparators, lower electrical power dissipation, and the opportunity to record the output on photographic film. Further work in modulator fabrication, mode-locked injection laser development, laser-to-modulator coupling techniques, and threshold optical detection techniques will be needed before the full potential of this device can be realized. Application areas include digital signal processors for wideband radar and electronic warfare systems.

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OBJECTIVES

Demonstrate the feasibility of performing analog-to-digital (A/D) conversion using integrated optical techniques, and carry out an investigation of competing approaches and potential applications for the integrated optical device.

RESULTS

1. An intensity modulator fabricated in lithium niobate was operated in a threshold circuit to simulate one bit channel of an optical A/D converter. Maximum phase shift with 28V peak-to-peak driving voltage was 24π radians for TE excitation, corresponding to 5.6 bits of precision.

2. The use of a repetitively pulsed light source is suggested as a unique means of signal sampling for the integrated optical device.

3. Potential advantages of the integrated optical device include a reduction in the number of comparators, lower electrical power dissipation, elimination of the sample-hold circuit, and the possibility of recording the output directly on photographic film.

4. Applications are seen in signal processing equipment for high-resolution radar, electronic warfare, spread spectrum communications, and intelligence data collection system.

RECOMMENDATIONS

Continue development of integrated optical A/D converter, with emphasis on modular techniques, mode-locked injection laser development, and high-speed threshold photodetectors.

CONTENTS

INTRODUCTION

Analog-to-digital converters are widely used to translate sensor measurements into the digital language of computing, information processing, and control systems.[1,2] In some military equipment, such as high-resolution radars, the capability to perform digital signal processing in real time is limited by the speed with which present A/D converters can function. Furthermore, although an electronic A/D converter with a conversion rate as high as 800 megawords/s (Mwords/s) has been demonstrated, the complexity, size, electrical power dissipation, and cost of these devices generally increase rapidly for conversion rates above about 25 Mwords/s.

Thus, new approaches which combine simplicity of design with the potential for high-speed operation have been sought, and several of those form the basis for active development efforts. These efforts encompass several different technologies: Schottky transistor-transistor logic (TTL) and emitter-coupled logic (ECL) in silicon, field-effect transistor (FET) and transferred electron device (TELD) logic in gallium arsenide, electron-beam semiconductor (EBS) techniques, and methods which employ superconducting Josephson-junction (JJ) logic elements.

Several schemes which make use of optical modulators or beam deflectors for performing A/D conversion have been proposed and investigated experimentally. The optical techniques seem to offer the potential for simpler design, lower power dissipation, and smaller size than conventional approaches, as well as the possibility of operation at conversion rates of 1 Gword/s or higher.

One of these approaches employs an array of electro-optic intensity modulators as the basic element of an A/D converter.[3,4] This report discusses the design of such a device, and presents the results of experiments designed to demonstrate the feasibility of the approach. Competing approaches and potential applications are also discussed.

DEVICE DESCRIPTION AND ANALYSIS

The basic circuit of the electro-optic A/D converter of the type described in this report is shown in figure 1. The circuit consists of a branching waveguide interferometric modulator,[5,6] a laser, a photodetector, and an electronic comparator. The A/D converter makes use of the fact that the output of the optical intensity modulator, the operation of which is based on a linear electro-optic phase retardation, varies in a periodic fashion as a function of an applied voltage. Similarly, each bit in the binary representation of an analog quantity is a periodic function of the value of that quantity.

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1. Hnatek, ER, A User's Handbook of D/A and A/D Converters, Wiley, New York, 1976, chapter 6
2. Sheingold, DH and Ferrero, RA, Understanding A/D and D/A Converters, IEEE Spectrum, vol 9, p. 47-56, September 1972
3. Taylor, HF, An Electro-optic Analog-to-Digital Converter, Proc. IEEE, vol 63, p. 1524-1525, October 1975
4. Lewis, DC and Taylor, HF, An Integrated Optical Analog-to-Digital Converter, NATO/AGARD Conference on Optical Fibers, Integrated Optics, and their Military Applications, London, May 1977
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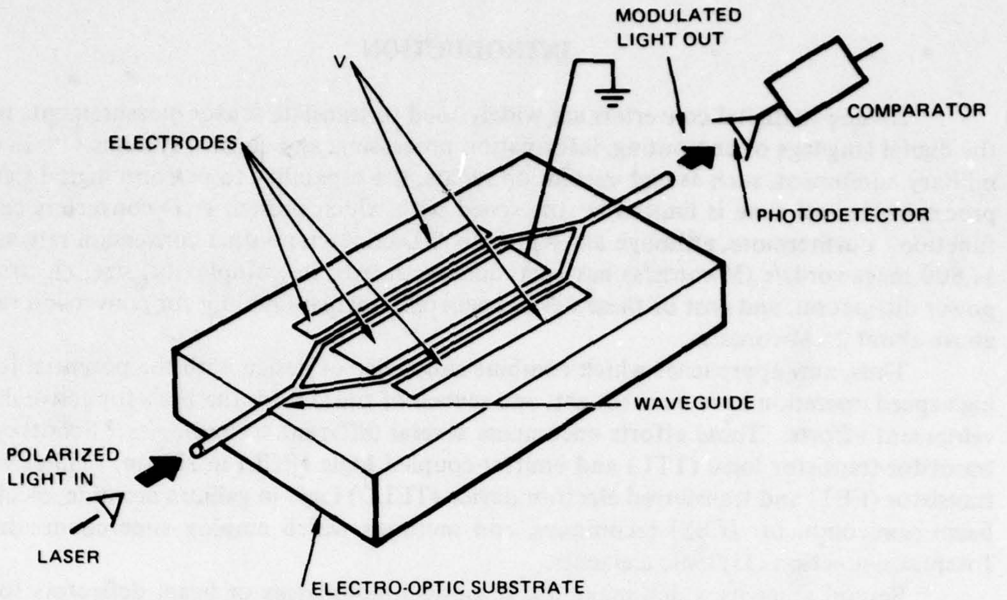

Figure 1. The basic optical circuit.

The proposed device, which takes advantage of this similarity, is illustrated schematically in figure 2. An array of modulators of the type illustrated in figure 1 is fabricated in a single-crystal substrate of a linear (Pockels) electro-optic material. Each waveguide, which can support one guided mode, is excited by linearly polarized light from a pulsed laser, as indicated in figure 2, or a cw laser. (The implications of using a pulsed laser are discussed in later sections.) A signal voltage V is applied across each waveguide. The electro-optic interaction length L_n for the n^{th} waveguide, as determined by the length of the signal electrodes, is given by

$$L_n = 2^{n-1} L_1,\ n = 1,2,3,\ldots$$

The phase of light in one branch is retarded with respect to that in the other branch of an amount of $\Delta\Gamma_n$ given by

$$\Delta\Gamma_n = 2^{n-1} K L_1 V\ .$$

The value of the constant K is determined by the electro-optic coefficients of the material, the waveguide parameters, and the electrode spacing. The intensity of light emerging from the n^{th} waveguide modulator is given by

$$I_n = A_n \cos^2 (\Delta\Gamma_n/2 + \psi_n/2) \quad (1)$$

where ψ_n is a static phase shift and A_n is the modulation amplitude.

The light emerging from each of the modulators is detected and amplified, and a binary representation of V is obtained by electronically comparing the intensity I_n with a threshold I_{nt}, and generating a "one" or "zero" for the n^{th} bit based on the outcome of the comparison. For example, an offset binary code for a bipolar signal is obtained if $\psi_n = \pi/4$ for each n by generating a "one" for the first bit if $I_{1t} \geqslant I_1$ and a "one" for the n^{th} bit,

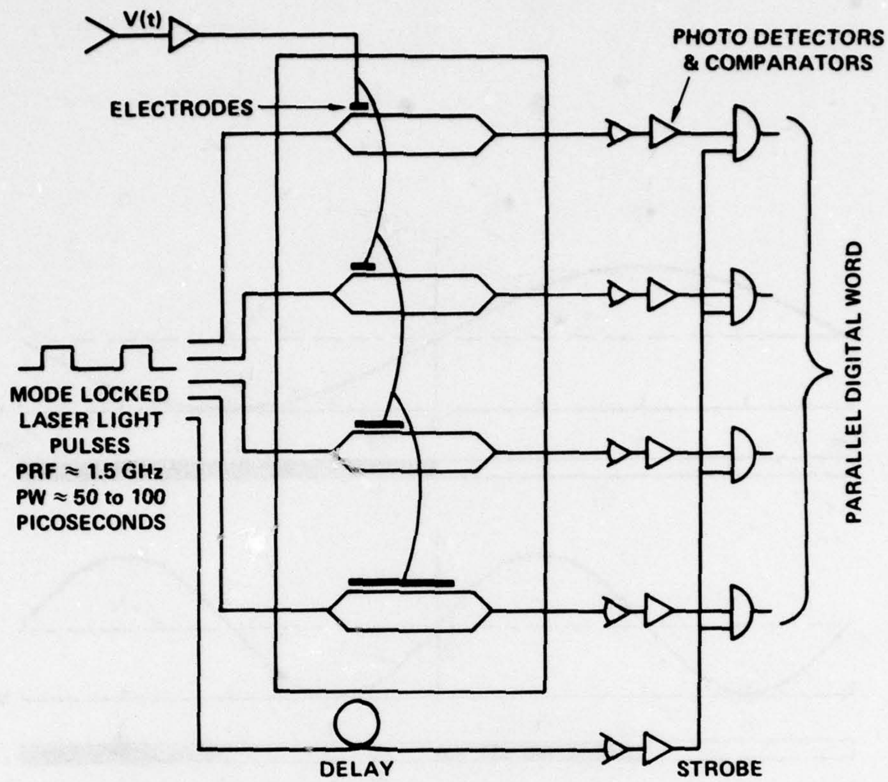

Figure 2. Schematic diagram of a three-bit electro-optic A/D converter.

$n = 2,3,\ldots$, if $I_n \geqslant I_{nt}$. The required values for the ψ_n's are obtained by applying a dc voltage V_{Dn} to a short section of waveguide in each modulator. The intensity I_n and the corresponding offset binary code are plotted as a function of V in figure 3 for a device with a 3-bit precision. It is evident from figure 3 that, as V changes, it is possible for two or even all three bits to change in value simultaneously. Significant errors in the conversion are most likely to occur for values of V near these intensity cross-over points. One way to avoid this problem is to use a Gray scale instead of a pure binary code. The only change from the offset binary device is in values for the static phase shifts (ψ_n's). Variations in the intensity components I_n for a four-bit Gray-scale converter are illustrated in figure 4. Since the value of only one bit changes for small variations in V, the probability of error in one of the most significant bits is greatly reduced. Furthermore, in a device of given length, one more bit of precision can be obtained with the Gray code than with the offset binary code.

The number of bits of precision, N, which can be obtained with a Gray code is related to the length of the waveguides according to

$$N = \log_2(\ell/\ell_\pi) + 2 \quad , \tag{2}$$

where ℓ_π is the minimum length required for a pi-radian electro-optic phase retardation. The formula

$$\ell_\pi = dV_\pi/2V_m \tag{3}$$

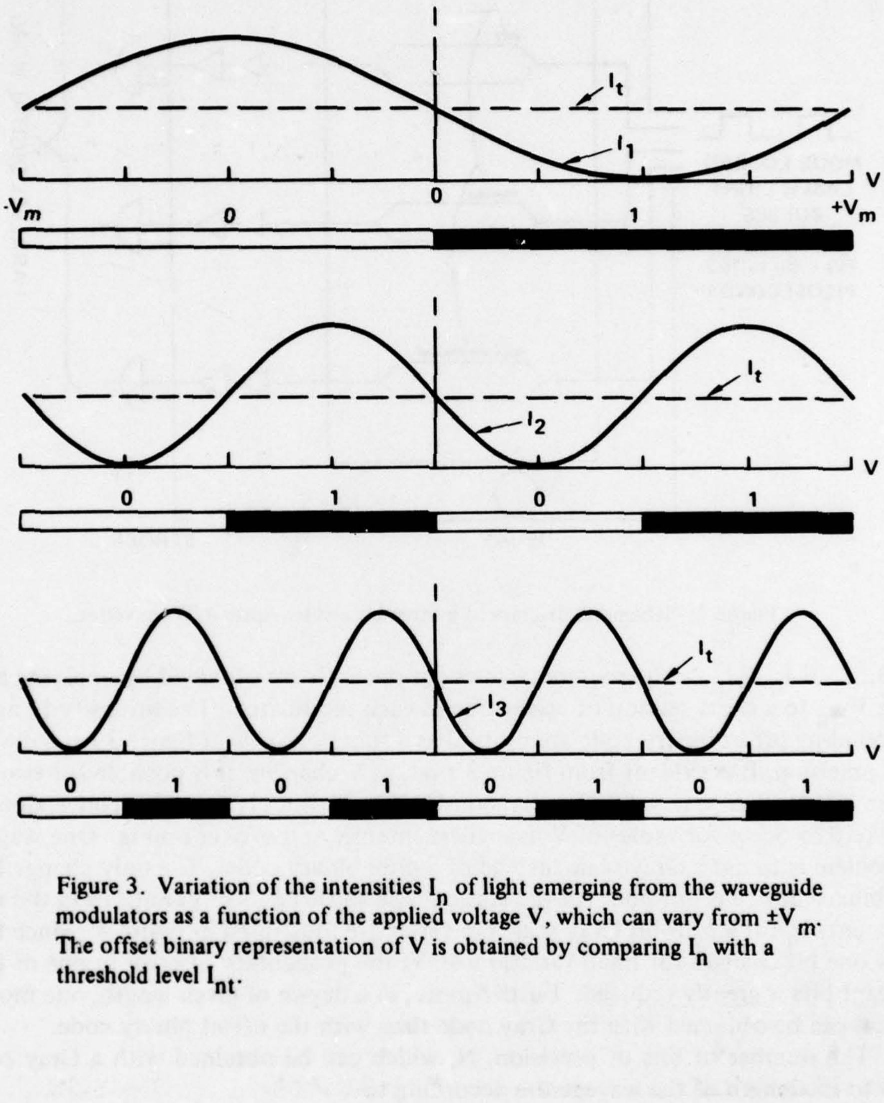

Figure 3. Variation of the intensities I_n of light emerging from the waveguide modulators as a function of the applied voltage V, which can vary from $\pm V_m$. The offset binary representation of V is obtained by comparing I_n with a threshold level I_{nt}.

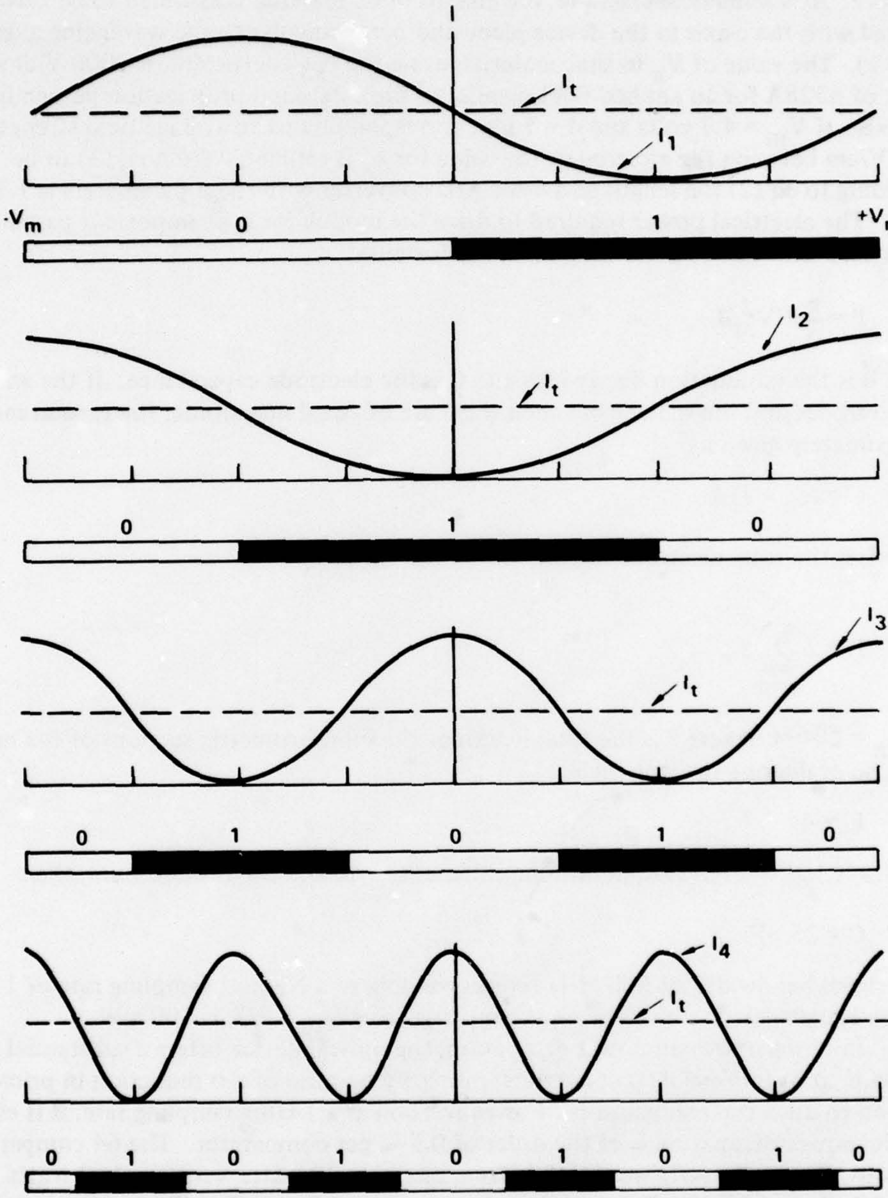

Figure 4. Intensity vs voltage plot for a four-bit A/D converter with Gray-scale output.

relates ℓ_π to the electrode spacing d, the half-wave voltage V of the material and the maximum applied voltage V_m. (It is assumed that V varies between $\pm V_m$). The factor of 2 in that equation arises from the fact that V is applied to both branches of the modulator structure. As a numerical example, the electro-optic material is assumed to be $LiNbO_3$, oriented with the c-axis in the device plane and perpendicular to the waveguide axes (see figure 1). The value of V_π in that material, using the r_{33} coefficient, is 2000 V at a wavelength of 6328Å for an applied field parallel to the c-axis and propagation perpendicular to that axis. If V_m = 4.7 volts and d = 5 μm, corresponding to an average field strength of 9600 V/cm between the electrodes, the value for ℓ_π is estimated from eq (3) to be 1.08 mm. According to eq (2) the length of a 6-bit A/D converter with these parameters is 1.7 cm.

The electrical power required to drive the modulator is an important parameter of the device. This can be calculated from the formula

$$P = \frac{\pi}{2} C V_m^2 B \quad ,$$

where B is the modulation bandwidth and C is the electrode capacitance. If the widths of the electrodes and the spacing between them are of equal magnitude, the capacitance is approximately given by

$$C = (\epsilon_o + \epsilon)\, L \quad ,$$

where L is the total electrode length, in this case given by

$$L = 2 \sum_{n=1}^{N} L_n \quad .$$

But $L_n = 2^{n-N}\ell$, where ℓ is the total length of the interferometric sections of the modulators, so evaluating the sum yields

$$L \sim 4\ell \quad .$$

$\epsilon_o = 8.9 \times 10^{-14}$ f/cm and, in lithium niobate, $\epsilon \sim 40\,\epsilon_o$. So, if ℓ = 1.7 cm, then

$$C = 25 \text{ pF} \quad .$$

For a signal bandwidth of 500 MHz (corresponding to a Nyquist sampling rate of 1 GHz), the power calculated from these equations, assuming V_m = 4.7, is 500 mW.

In terms of overall power dissipation, the optical device offers a substantial improvement over conventional A/D converters, primarily because of the reduction in prime power required to drive the comparators. For conversion at a 1-Gb/s sampling rate, it is estimated that the power dissipation is of the order of 0.5 W per comparator. The 64 comparators in an electronic parallel A/D would, therefore, dissipate 32 watts, versus only 3 watts for the optical device. Assuming 0.3 watt for a laser source, 0.2 watt for the electro-optic portion of the device, and 0.6 watt each for the 6 photodetector/amplifiers raises the total to only 7.2 watts for the optical device.

A limiting factor in implementing fast A/D converters, either electronic or electro-optic, is the speed of the analog comparator. Present commercial devices operate at a rate less than 4×10^8 comparisons per second, although continuing improvements in high-speed

logic devices encourage us to anticipate faster comparators in the near future. An interesting possibility would be to use a transferred electron device (TELD) as the photodetector. The TELD (Gunn-effect) device would be biased slightly below threshold for oscillation. Carriers generated by the incident optical pulse would initiate the propagation of a charge domain, provided that the optical power level exceeded a threshold determined by the bias voltage. Thus, the TELD device would function as a threshold photodetector for optical signals. In a previous experiment using a mode-locked helium-neon laser source, instrument-limited rise times of less than 1 ns were observed.[7]

EXPERIMENTAL RESULTS

The basic element in the optical A/D converter is the channel waveguide interferometric modulator. An experiment was therefore carried out in which modulators of that type were fabricated in lithium niobate and operated in a threshold circuit to simulate a bit channel in an A/D converter.[8]

The experimental arrangement is ilustrated in figure 5. The linearly polarized 0.63 μm output of the CW HeNe laser is coupled by a microscope objective into an interferometric optical modulator fabricated in lithium niobate. The time varying voltage V is applied to the modulator electrodes. The intensity-modulated light is detected by a silicon avalanche photodiode, and the amplifier output drives an electronic comparator. The temporal variation in the modulating voltage, photodetector output, and comparator output is displayed on an oscilloscope.

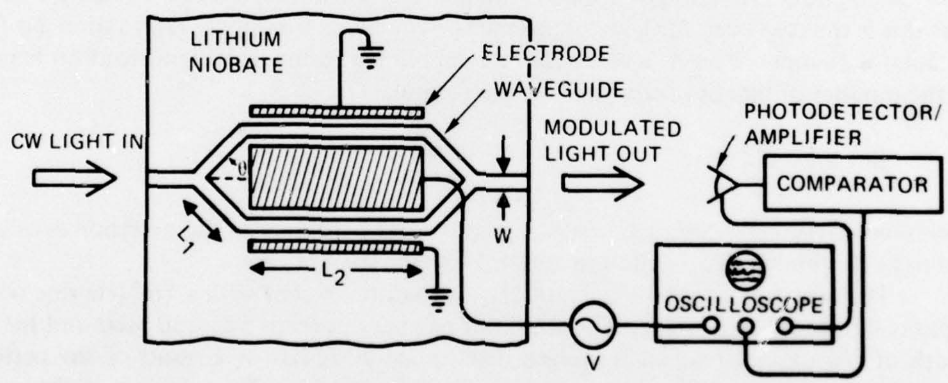

Figure 5. Experimental arrangement for operation of the electro-optic modulator in a threshold circuit.

7. Adams, RF and Schulte, HJ, Optically Triggerable Domains in GaAs Gunn Diodes, Appl. Phys. Lett., vol 15, p. 265-267, October 15, 1969
8. Taylor, HF, Taylor, MJ, and Bauer, PW, Electro-optic Analog-to-Digital Conversion Using Channel Waveguide Modulators, App. Phys. Lett., vol 32, p. 559-561, May 1, 1978

Waveguides for the modulator are fabricated by titanium diffusion into a Y-cut lithium niobate substrate. After deposition of a titanium layer 400Å ± 50Å thick on the substrate, the waveguide pattern is produced in photoresist by photolithography with the waveguide axes oriented normal to the optic axis of the crystal. The titanium is then etched, using hydrofluoric acid, and the photoresist removed to leave the pattern in the titanium film. The substrate is heated for 4 hours at 960°C in flowing argon, followed by 1 hour at that temperature in oxygen. An aluminum layer is then deposited and the electrode pattern produced by photolithography. Finally, the ends of the crystal normal to the waveguide axes are cleaved to produce mirror surfaces for optical coupling.

The waveguide pattern, illustrated in figure 5, is made up of identical straight sections of waveguide. Dimensions for the branching waveguide structure are L_1 = 1.5 mm, L_2 = 17 mm, and θ = .01 radians. Widths of the titanium stripes, prior to diffusion, range from 5 μm to 10 μm, the electrode spacing is 2 μm greater than the stripe width, and the overall length of the cleaved crystal is about 25 mm.

Experimental results for one of the modulators driven by a 60-kHz sawtooth waveform with peak-to-peak voltage of 28 volts are given in figure 6. The pre-diffusion stripe width was 8 μm. The total phase shift for TE excitation (polarization parallel to the surface of the substrate) was 24 π radians, and for TM excitation (polarization perpendicular to the surface) was 9 π radians. The corresponding voltages for pi-radian phase shift (maximum modulation) were 1.2 volts for TE polarization and 3.1 volts for the TM case. Similar results were obtained for several other modulators studied. Typical insertion losses were 10–15 dB for both polarizations, and modulation depths were 90–95% for TM and 40–60% for TE excitation.

If modulators of this type are to be used for A/D conversion, the output intensity must be a periodic function of applied voltage. The oscilloscope traces of figure 6 indicate that this is the case even for large phase shifts. The maximum phase retardation $\Delta\phi$ for the modulator channel of an A/D converter corresponding to the least significant bit is related to the number of bits of precision N by the formula

$$N = \log_2 \frac{\Delta\phi}{\pi} + 1 \quad , \tag{5}$$

assuming a Gray scale coding scheme. From the data of figure 6, the precision is calculated to be 5.6 bits for TE excitation and 4.2 bits for the TM case.

Performance of one of the modulators (width = 6 μm) with a 16-MHz sine wave input is illustrated in figure 7. The amplifier passband is from 5 to 250 MHz and the bandwidth of the detected signal is increased to about 200 MHz as a result of the periodic intensity vs voltage response characteristic of the modulator. The response of the emitter-coupled logic (ECL) comparator, which has rise and fall times of 3 ns, is also shown.

In order to operate an A/D converter at high speeds, some technique for sampling the analog input signal is needed. For the electro-optic A/D converter, the data of figure 7 illustrates that, without sampling, the bandwidth of the analog driving signal must be much less than the comparator bandwidth. With sampling, the signal bandwidth can be comparable to that of the comparator. The conventional approach is to use an electronic sample-to-hold device to sample the incoming signal at fixed time intervals and maintain the value of the sample during the time needed to perform a comparison. However, drift in the sample-to-hold circuit can seriously degrade converter performance. A more elegant solution in the optical case would be to use a repetitively pulsed or mode-locked laser as

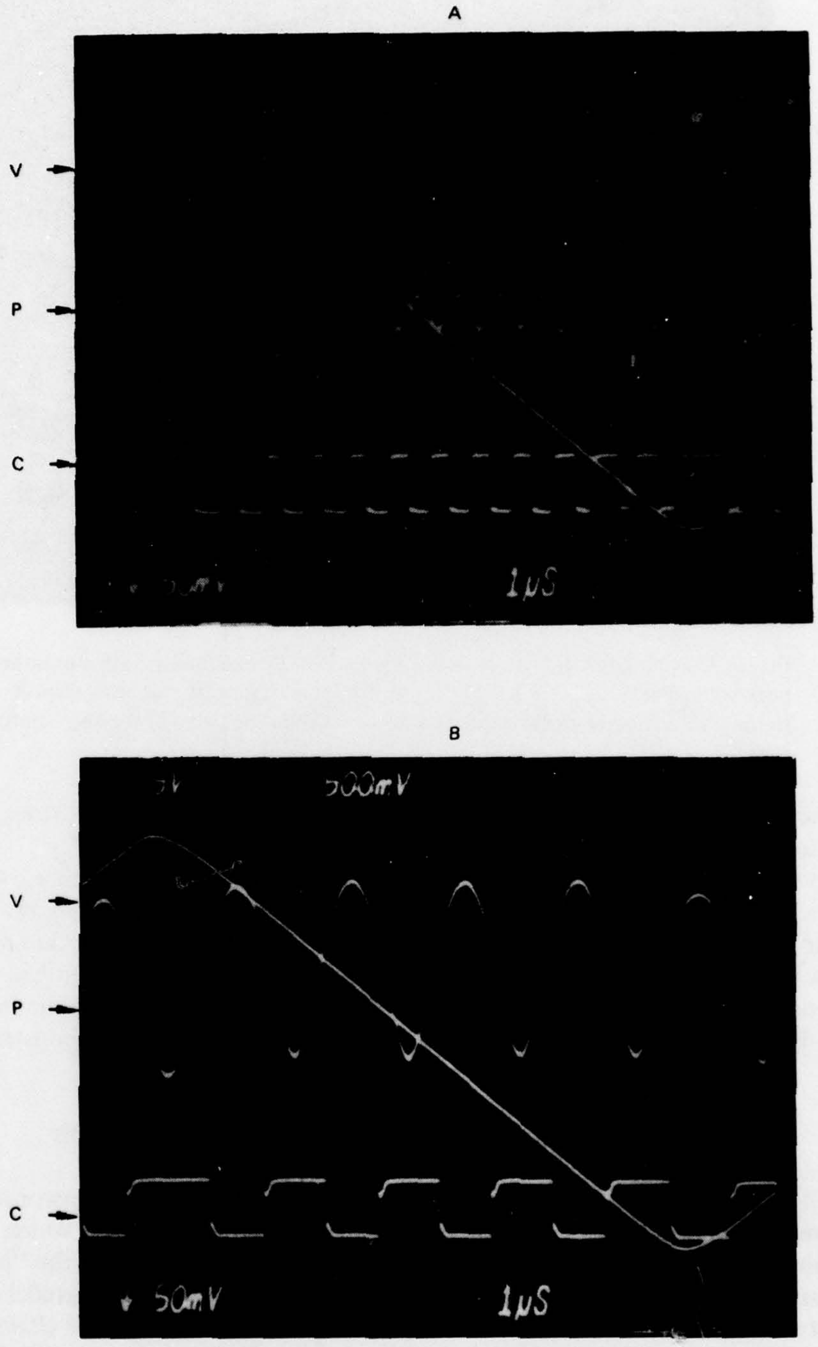

Figure 6. Temporal dependence of modulator and comparator response for TE excitation (top trace) and TM excitation (bottom trace), for peak-to-peak driving voltage variation of 28 volts: V = modulating voltage, P = photodetector output, C = comparator output.

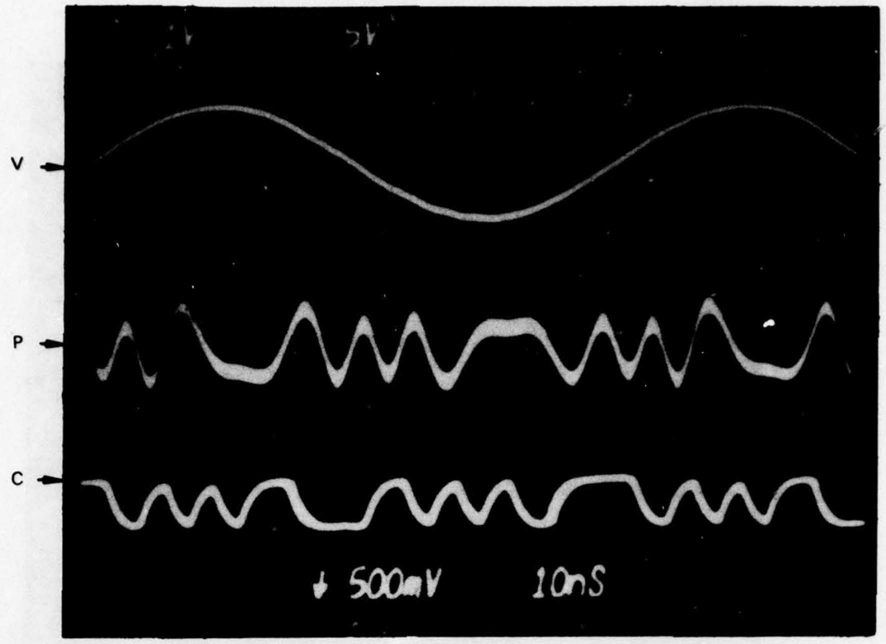

Figure 7. Modulator and comparator response for TE excitation, with a peak-to-peak voltage variation of 8 V. The lag in the comparator response with respect to the photodetector signal is due to a 15-ns propagation delay in the comparator circuit.

the light source. If the pulse width is sufficiently short, the pulse itself provides the time window during which the signal on the modulator electrodes is sampled.

In summary, experimental results illustrating the periodic dependence of the output of an optical waveguide modulator on applied voltage for phase retardations as large as 24 π radians have been presented. The use of a relatively long (17 mm) modulation region made it possible to achieve a π-radian voltage of 1.2 volts, significantly lower than had been reported previously in modulators of this type.[5,6] The operation of the modulators in a threshold circuit to simulate a bit channel in an electro-optic A/D converter was demonstrated.

ALTERNATIVE TECHNIQUES FOR A/D CONVERSION

The most common method for performing high-speed (>25 megawords/second) A/D conversion is to compare the input voltage V with reference voltages which correspond to different levels in the digital representation of V. This is referred to as the "parallel" method, since all the comparisons are done simultaneously. A three-bit parallel converter is illustrated in figure 8. The reference voltages, which are set by a resistor chain, are each supplied as an input to an analog comparator. The input voltage is supplied through a second resistor chain as the other input to each comparator. The high speed results from the fact that all of the comparisons are done in parallel, but a large number of comparators (2^N-1 for an N-bit converter) are needed to accomplish this. Furthermore, electronic logic elements are required to convert the comparator outputs to a binary representation of V.

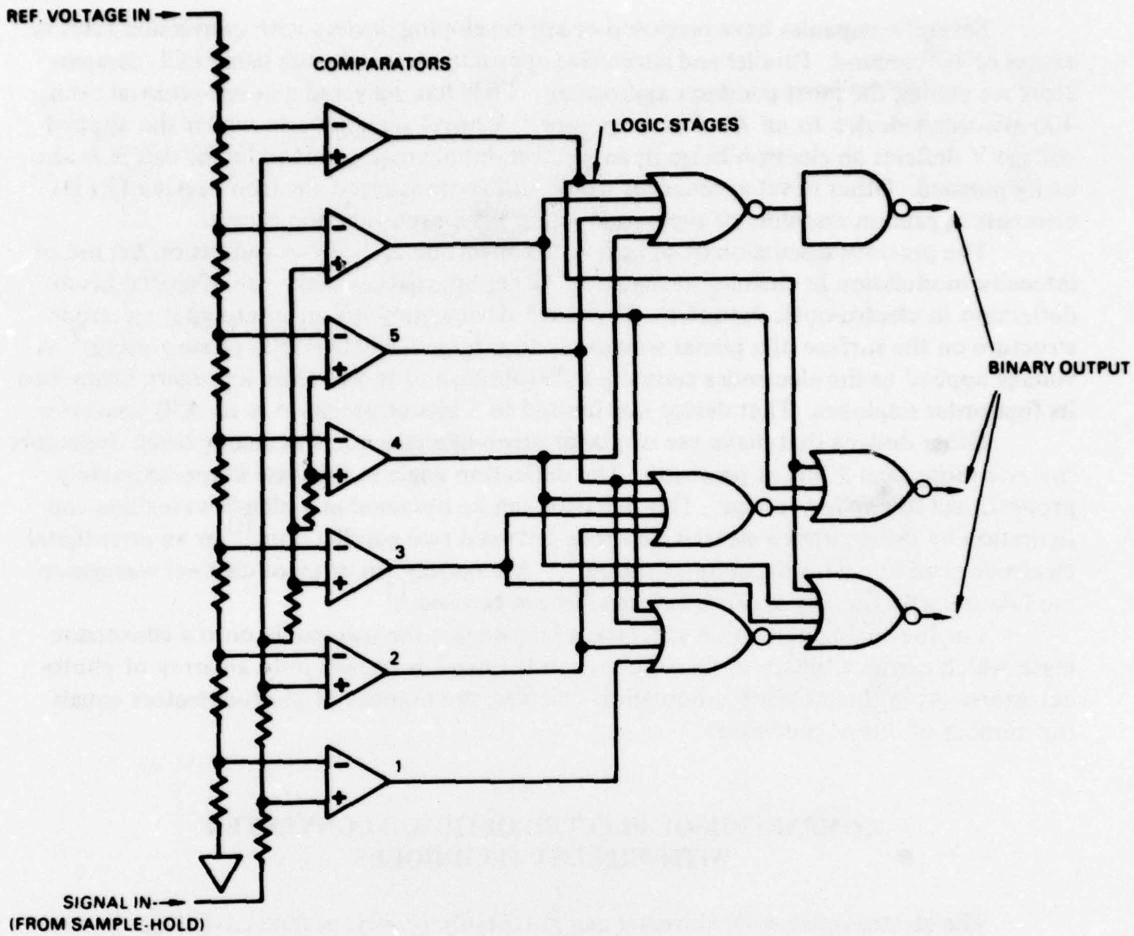

Figure 8. Schematic diagram of an electronic parallel A/D converter with three bits of precision.

Open-loop successive approximation is a technique for "pipelining" the conversion process by computing the most significant bits first and determining the reference voltage for each subsequent bit from the comparator outputs for previously computed bits. A time delay is required to allow for the computation of the most significant bits before V is applied to the comparators which compute less significant bits. Only N comparators are required with this method, but the synchronization problems are more severe and the time delay between input and output is considerably greater than with the completely parallel approach.

The fastest devices commercially available at the present time perform 10^8 conversions/second with 6–8 bits of precision. A device marketed by TRW utilizes two interleaved converters, each of which operates at 5×10^7 conversions/second and utilizes both parallel and serial logic with ECL comparators. Also, Biomation and Phoenix supply converters with conversion rates of 10^8 words/sec; both use parallel conversion schemes. The Biomation device uses TTL comparators while the Phoenix device employs ECL. Aeroflex has developed an 800 Mwords/s 6-bit A/D converter. The Aeroflex system uses an interleaved parallel conversion scheme and ECL logic; the system requires roughly 1 kW prime power.

Several companies have proposed or are developing devices with conversion rates in excess of 10^8/second. Parallel and successive-approximation schemes using ECL comparators are among the most common approaches. TRW has delivered a developmental 5-bit, 400-Mwords/s device to an Air Force sponsor. A novel technique in which the applied voltage V deflects an electron beam in an electron-bombarded semiconductor device is also being pursued. Other novel approaches would utilize transferred electron device (TELD) elements in gallium arsenide, or superconducting Josephson-junction arrays.

The previous discussion of optical A/D conversion techniques centers on the use of intensity modulation in channel waveguides. Other approaches make use of spatial beam deflection in electro-optic materials. One such device employs an interdigital electrode structure on the surface of a planar waveguide to set up an electro-optic phase grating.[9] A voltage applied to the electrodes caused a redistribution of power from a primary beam into its first-order sidelobes. That device was limited to 3 bits of precision as an A/D converter.

Other designs that make use of planar prism-like structures as analog beam deflectors can give more than 3 bits of precision. The deflection angle in this case is approximately proportional to applied voltage. This behavior can be obtained in a planar waveguide configuration by using either a slanted electrode between two parallel ones[10] or an interdigital electrode structure with linear apodization.[11] Alternately, an array of channel waveguide modulators with linearly apodized electrodes can be used.[11]

For the analog deflection schemes, a lens images the waveguide onto a conversion mask which carries a binary or Gray code, and the mask is imaged onto an array of photodetectors. As in the intensity modulation schemes, the number of photodetectors equals the number of bits of precision.

COMPARISON OF ELECTRO-OPTIC A/D CONVERTER WITH PRESENT TECHNIQUES

The electro-optic A/D converter can potentially provide several advantages in comparison with conventional fast parallel A/D converters. First, the number of comparators would be dramatically reduced, from 2^N to N, for an N-bit converter (eg, from 64 to 6 for a 6-bit converter). This would substantially reduce the electrical power drain of the unit (~200 MW each for commercial 200-MHz ECL comparators) and would greatly simplify the timing problems which occur in electronic converters because of the large number of comparators.

Another advantage of the optical device is that the use of a repetitively pulsed (mode-locked) laser source could eliminate the need for a sample-and-hold device. The function of a sample-and-hold in an A/D converter is to sample the signal at fixed time intervals and maintain the value of the sampled signal during the time a conversion takes place. The output of the sample-and-hold is the voltage input to the device which actually performs the conversion. The drift of the sample-and-hold must be less than $2^{-(N+1)}$

9. Wright, S, Mason, IM and Wilson, MGF, High-Speed Electro-optic Analog-to-Digital Conversion, Electron. Lett., vol 10, p. 508-509, November 24, 1974
10. Giallorenzi, TG, An Overview of Micro-optic Signal Processing Research, IEEE/OSA Topical Meeting on Integrated and Guided Wave Optics, Salt Lake City, January 1978, paper MA1
11. Saunier, P, Tsai, CS, Yao, IW, and Nguyen, LT, Electro-optic Phased-Array Light Beam Deflector with application to Analog-to-Digital Conversion, IEEE/OSA Topical Meeting on Integrated and Guided Wave Optics, Salt Lake City, January 1978, paper TUC2

times the full voltage swing to obtain N bits of precision, and the jitter in the sampling clock must be less than $2^{-(N+1)}$ times the conversion period; eg, 8 ps for a 1-Gword/s, 6-bit converter. With a short optical pulse, the width of the pulse would provide a time window for performing a sampling operation. It has been calculated that a 100-ps pulse width would be short enough for a 1-Gword/s, 6-bit converter.

An injection laser diode, because of its small size and low electrical power dissipation, would be an ideal optical source for the A/D converter. Results of a recent experiment in which an injection laser diode was mode-locked with a 20-ps pulse width and a 3-GHz repetition rate[12] are quite encouraging from that standpoint, although pulse-to-pulse jitter was not measured in that experiment. It is clear that additional work will be needed to perfect mode-locked lasers suitable for use with the optical A/D converter.

A final feature of the optical A/D converter is that the output can be recorded directly upon photographic film. This would make it possible to collect, digitize, and make a permanent record of data at a very high rate. The data could then be processed later at more convenient speeds.

A summary of critical characteristics of the electro-optic A/D converter is presented in table 1.

Table 1. High-speed electro-optic A/D converter – summary.

Present method: High-speed electronic logic

Elements of integrated optics device:

- Array of modulators on electro-optic substrate
- Injection laser source
- Sample-and-hold interface
- Avalanche photodiode detectors } or TELD threshold photodetectors
- Electronic comparators }

Potential advantages of integrated optics device:

- Fewer comparators (N versus 2^N-1)
- No sample-and-hold with pulsed light source
- Lower electrical power dissipation
- Optical output can be recorded directly on film

Disadvantages

- Development needed
- Not cost competitive at low (~25-megaword/second) conversion rates
- Limited to about 8 bits of precision for parallel operation

12. Ho, PT, Glasser, LA, Ippen, EP, and Haus, NA, to be published

Table 1. (Continued).

Performance-limiting factors:

Present comparators operate at 400 MHz

Speed of avalanche photodiodes limited to ~3 GHz

Potential Performance:

Near-term (1-3 years) 400 megaword/second, 6 bits

Intermediate term (3-6 years) 1 gigaword/second, 6-8 bits

Major technology development needed:

Multichannel modulator fabrication

Mode-locked lasers

Laser-modulator coupling techniques

Faster comparators

POTENTIAL APPLICATIONS

A number of military systems have been identified as potential application areas for an electro-optic A/D converter.[13] These are for the most part systems in which signal processing performance is limited by the speed of present electronic converters.

Signal processors for high-resolution radars (HRR) with a bandwidth which is typically of the order of 500 MHz, could make effective use of faster A/D capability in several ways. The range resolution of real-time synthetic aperture radars is inversely proportional to the conversion rate. An increase in conversion rate from 100 Mwords/s to 500 Mwords/s, for example, would improve range resolution from about 3 meters to about 0.6 meter. Faster conversion rates would make it possible to perform monopulse HRR imaging on a pulse-by-pulse basis, rather than by sampling a large number of successive pulses to reconstruct a single return signal. Target classification would also be aided by the improved resolution available to a digital processor. High-speed A/D's would also be useful as a means of discriminating true returns from those generated by repeater jammers. A final HRR application would involve the use of the optical A/D in conjunction with a fiber delay line for pulse-to-pulse integration as a means of clutter suppression. Such a radar processing technique could be used, for example, for obstacle avoidance for high-speed surface-effect ships.

Two examples of how high-speed A/D converters might be used in electronic warfare (EW) systems are illustrated in figure 9 and figure 10. The optical analog-to-digital converter operating at Gword/s rates combined with long recirculating fiber optic delay-line memory loops can store broadband (300 to 500 MHz) signal data excerpts (1000 to 2000 microseconds) for indefinite periods of time (see figure 9). This would provide the capability to analyze repetitively a time slice of signal spectrum in an adaptive hypothesis testing manner. Airborne systems could use this technique for fine-grain pulse analysis and signature recognition.

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13. Dillard, GM, Taylor, HF, and Hunt, Barry R, Fiber and Integrated Optic Techniques for Radar and Communications Signal Processing, National Telecommunications Conference, Dallas, November 1976

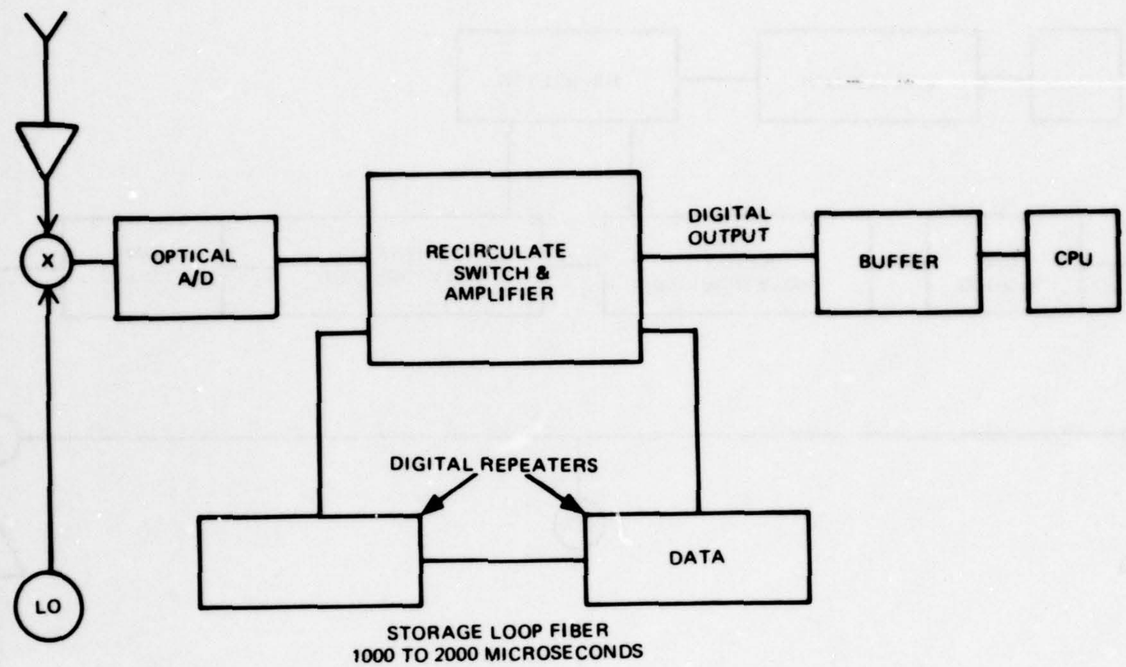

Figure 9. Recirculating loop fine-grain-analysis ESM receiver.

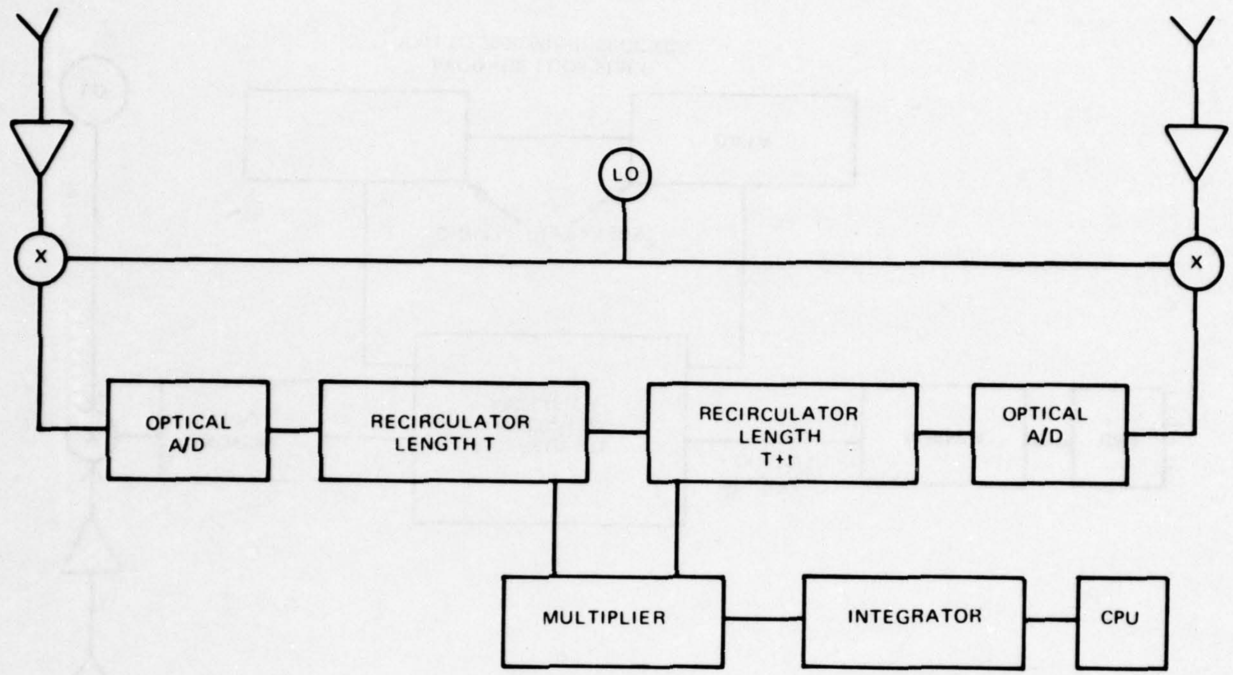

Figure 10. Time difference of arrival by broadband cross correlation.

An extension of the recirculating spectrum storage technique utilizing a two-channel receiver (see figure 10) could compute direction of arrival (DOA) on spread-spectrum signals utilizing cross correlation or convolution to derive time difference of arrival. This method has the advantage of substantial signal-to-noise improvement (because of signal autocorrelation) over leading-edge gating and carrier-frequency independence, as well as signal-to-noise improvement over interferometer techniques. The technique would be useful primarily with signals above 500 MHz, with bandwidths in excess of 100 MHz.

Another interesting application of the optical A/D converter is in intelligence data collection. In this case, it might prove expedient to eliminate the photodetectors and subsequent electronics and to record the optical output of the modulator chip directly on fast-moving film.

CONCLUSIONS

The periodic dependence of the output of an electro-optic intensity modulator on applied voltage can be utilized to perform A/D conversion. The feasibility of the concept has been demonstrated by such a modulator in a threshold circuit to simulate one bit channel of an A/D converter. The optical approach offers several potential improvements over present technique: faster conversion rates, fewer comparators, lower electrical power dissipation, and the opportunity to record the output on photographic film. Further work in modulator fabrication, mode-locked injection laser development, laser-to-modulator coupling techniques, and threshold optical detection techniques will be needed before the full potential of this device can be realized. Military application areas include digital signal processors for wideband radar and electronic warefare systems.

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